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THE IDEAL EFFICIENCY OF OPTIMUM PROPELLERS HAVING FINITE HUBS AND FINITE NUMBERS OF BLADES

by

CDR. J. W. Schultz, Jr., USN

HYDRODYNAMICS LABORATORY

RESEARCH AND DEVELOPMENT REPORT

July 1957 Report No. 1148

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Notation

C_{T_i}	Ideal (non-viscous) thrust coefficient
h	Subscript denoting finite hub
$K_{mn}^{(Z)}$	Integral defined by equation (2)
r	Section radius
R	Propeller tip radius
$X = \frac{r}{R}$	Nondimensional section radius
X_h	Non-dimensional hub radius
Z	Number of Blades
β_i	Hydrodynamic pitch angle
η_i	Ideal efficiency
λ	Advance coefficient
λ_i	Induced advance coefficient ($= \frac{\lambda}{\eta_i} = X \tan \beta_i$)
κ	$= \kappa(\lambda_i, Z, X, X_h)$ "Goldstein Factor" or "Circulation Distribution Factor" from reference (8)

Abstract

The ideal (non-viscous) thrust coefficient C_{T_i} related to a range of ideal efficiencies (η_i) and a range of advance coefficients (λ) is calculated for propellers having 3, 4, 5 and 6 blades and having hubs whose diameters are 0.2, 0.3 and 0.4 of the propeller diameter.

Introduction

The relationships between ideal (non-viscous) thrust coefficient C_{T_i}, ideal efficiency η_i and advance coefficient λ for propellers having a finite number of blades but zero hub diameter were determined by Kramer[1] after suitably transforming equations (8) and (11) of Lösch[2] for finite blade number. The results obtained were based on Goldstein's[3] solution of the potential problem, recalculated by Lock,[4] and Yeatman[4] and Kramer, himself, and extended by Kramer for large values of λ_i.

When Lerbs[5] published a propeller design method using "induction factors," it became possible to compare theoretically the circulation distributions for lightly and moderately loaded propellers. When, as a result of

[1] References are listed on page 5

this comparison, it was seen that the condition of normality for lightly loaded propellers could be applied to moderately loaded propellers with good accuracy, "it was then deemed necessary to determine the Goldstein Factor by more accurate methods than had previously been used, particularly for sections near the tip and for large advance ratios."[6] This was done by Tachmindji and Milam.[6]

Noting the increasing use of propellers with relatively large hubs, Tachmindji[7] formulated and solved the potential problem for propellers with finite hub diameters. Numerical evaluations are presented by Tachmindji and Milam.[8]

Herein are given relationships between ideal (nonviscous) thrust coefficient C_{T_i}, ideal efficiency η_i (=0.50, 0.60, 0.70, 0.80, 0.85, 0.90, 0.95, 0.97, 0.99) and $\lambda = \lambda_i \eta_i$. Kramer's work is thus extended for propellers having finite hubs.

Method of Computation

The basic equation for the computation is Kramer's equation (1.1) (notation is changed to agree with that in use at the David Taylor Model Basin):

$$C_{T_i} = \frac{8(1-\eta_i)}{\eta_i} K_{31}^{(Z)} + \frac{8(1-\eta_i)^2}{\eta_i^3} K_{52}^{(Z)} \qquad (1)$$

$$K_{mn}^{(Z)} = \int_{x_h}^{1} \frac{\kappa X^m}{(\lambda_i^2 + X^2)^n} dX \qquad (2)$$

where C_{T_i} = ideal thrust coefficient

η_i = ideal efficiency

$\kappa = \kappa(\lambda_i, Z, X, X_h)$ = "Goldstein Function" or "Circulation Distribution Factor" from reference (8)

$\lambda_i = X \tan \beta_i = \frac{\lambda}{\eta_i}$

β_i = hydrodynamic pitch angle

λ = advance ratio

Z = number of blades

$X = \frac{r}{R}$ nondimensional section radius

$X_h = \frac{\text{hub diameter}}{\text{propeller diameter}}$

h = subscript denoting finite hub

The integrations of $K_{mn}^{(Z)}$ were performed using a desk computer and Simpson's first and second rules.

Presentation of Results

Curves relating C_{T_1}, η_i and λ for 3, 4, 5 and 6 bladed propellers having 0.2, 0.3 and 0.4 hub diameter ratios are given in Figures 1-4 Appendix B. In addition, curves taken from Kramer's curves for zero hub and 4 bladed are plotted on Figure 2 in order to show a comparison with propellers having finite hubs.

For more convenient use in interpolating for values of λ_i and X_h between those given, Tables 1-4, Appendix A, give values of C_{T_1} as a function of Z, λ_i, η_i and X_h.

The results presented are considered accurate within one in the third significant figure throughout the range covered.

References

1. Kramer, K. N., "Induzierte Wirkungsgrade von Best-Luftschrauben endlicher Blattzahl," Luftfahrtforschung, Vol. 15, no. 7, July 6, 1938.

2. Losch, F., "Über die Berechnung des induzierten Wirkungsgrades stark belosteter Luftschrauben unendlicher Blattzahl," Luftfahrtforschung, Vol. 15, no. 7, July 6, 1938.

3. Goldstein, S., "On the Vortex Theory of Screw Propellers," Proceedings Royal Society, Vol. 123A, 1929.

4. Lock, C. N. H., and Yeatman, D. M., "Tables for Use in an Improved Method of Airscrew Strip Theory Calculation," R. and M. No. 1674, British A.R.C., 1935.

5. Lerbs, H. W., "Moderately Loaded Propellers with a Finite Number of Blades and an Arbitrary Distribution of Circulation," Trans. SNAME, 1952.

6. Tachmindji, A. J., and Milam, A. B., "The Calculation of Goldstein Factors for Three, Four, Five and Six Bladed Propellers," DTMB Report No. 1034, March 1956.

7. Tachmindji, A. J., "The Potential Problem of the Optimum Propeller with Finite Hub", DTMB Report No. 1051, August 1956, and International Shipbuilding Progress, November 1956.

8. Tachmindji, A. J., and Milam, A. B., "The Calculation of the Circulation Distribution for Propellers with Finite Hub Having Three, Four, Five and Six Blades," DTMB Report No. 1141, June 1957.

Appendix A

Tables of $C_{T_i} - \eta_i - 1/\lambda_i$ for 3,4,5 and 6 bladed propellers

Table I

Ideal Thrust Coefficient, C_{T_i}, for THREE-BLADED Propellers

η_i \ $1/\lambda_i$	3.0	3.5	4.0	4.5	5.0	5.5	6.0
				$x_h = 0.2$			
0.50	3.3514	3.8587	4.2842	4.6338	4.9356	5.1848	5.3954
0.60	1.9089	2.1860	2.4177	2.6104	2.7715	2.9066	3.0208
0.70	1.0777	1.2278	1.3529	1.4567	1.5434	1.6160	1.6774
0.80	0.5632	0.6386	0.7011	0.7529	0.7961	0.8322	0.8627
0.85	0.3786	0.4282	0.4693	0.5033	0.5316	0.5553	0.5753
0.90	0.2278	0.2570	0.2812	0.3011	0.3178	0.3317	0.3434
0.95	0.1034	0.1164	0.1271	0.1360	0.1433	0.1495	0.1547
0.97	0.0598	0.0672	0.0734	0.0784	0.0827	0.0862	0.0892
0.99	0.0192	0.0216	0.0236	0.0252	0.0265	0.0276	0.0286
				$x_h = 0.3$			
0.50	3.0441	3.5161	3.9152	4.2510	4.5316	4.7690	4.9696
0.60	1.7296	1.9876	2.2053	2.3882	2.5409	2.6700	2.7792
0.70	0.9742	1.1140	1.2318	1.3306	1.4130	1.4826	1.5414
0.80	0.5080	0.5782	0.6372	0.6866	0.7278	0.7626	0.7919
0.85	0.3411	0.3873	0.4261	0.4586	0.4857	0.5085	0.5278
0.90	0.2050	0.2322	0.2551	0.2742	0.2901	0.3035	0.3149
0.95	0.0929	0.1051	0.1152	0.1237	0.1308	0.1367	0.1418
0.97	0.0537	0.0607	0.0665	0.0714	0.0754	0.0788	0.0817
0.99	0.0173	0.0195	0.0213	0.0229	0.0242	0.0252	0.0262
				$x_h = 0.4$			
0.50	2.6321	3.0563	3.4218	3.7291	3.9965	4.2214	4.4142
0.60	1.4917	1.7240	1.9239	2.0918	2.2380	2.3608	2.4662
0.70	0.8381	0.9643	1.0727	1.1637	1.2429	1.3095	1.3665
0.80	0.4361	0.4995	0.5540	0.5996	0.6394	0.6728	0.7014
0.85	0.2924	0.3343	0.3702	0.4002	0.4264	0.4484	0.4673
0.90	0.1755	0.2002	0.2214	0.2391	0.2546	0.2675	0.2786
0.95	0.0795	0.0905	0.0999	0.1078	0.1147	0.1204	0.1254
0.97	0.0459	0.0522	0.0576	0.0622	0.0661	0.0694	0.0722
0.99	0.0148	0.0168	0.0185	0.0199	0.0212	0.0222	0.0231

Table II

Ideal Thrust Coefficient, C_{T_i}, for FOUR-BLADED Propellers

η_i \ $1/\lambda_i$	3.0	3.5	4.0	4.5	5.0	5.5	6.0
			$x_h = 0.2$				
0.50	3.7639	4.2684	4.6787	5.0142	5.2882	5.5150	5.7034
0.60	2.1434	2.4176	2.6401	2.8214	2.9693	3.0915	3.1931
0.70	1.2098	1.3577	1.4772	1.5743	1.6534	1.7188	1.7730
0.80	0.6322	0.7060	0.7655	0.8136	0.8528	0.8851	0.9119
0.85	0.4249	0.4734	0.5124	0.5439	0.5695	0.5906	0.6081
0.90	0.2596	0.2861	0.3069	0.3254	0.3404	0.3528	0.3630
0.95	0.1160	0.1278	0.1388	0.1469	0.1535	0.1590	0.1635
0.97	0.0671	0.0743	0.0801	0.0848	0.0885	0.0917	0.0942
0.99	0.0216	0.0239	0.0257	0.0272	0.0284	0.0294	0.0302
			$x_h = 0.3$				
0.50	3.4914	3.9646	4.3505	4.6647	4.9212	5.1331	5.3117
0.60	1.9836	2.2410	2.4504	2.6206	2.7594	2.8739	2.9706
0.70	1.1172	1.2560	1.3686	1.4600	1.5344	1.5959	1.6477
0.80	0.5826	0.6519	0.7080	0.7534	0.7903	0.8208	0.8465
0.85	0.3912	0.4367	0.4735	0.5032	0.5274	0.5474	0.5642
0.90	0.2351	0.2618	0.2834	0.3009	0.3150	0.3267	0.3366
0.95	0.1066	0.1184	0.1280	0.1357	0.1420	0.1472	0.1515
0.97	0.0616	0.0684	0.0739	0.0783	0.0819	0.0848	0.0873
0.99	0.0198	0.0220	0.0237	0.0251	0.0262	0.0272	0.0280
			$x_h = 0.4$				
0.50	3.0981	3.5309	3.8893	4.1823	4.4244	4.6256	4.7967
0.60	1.7598	1.9927	2.1868	2.3461	2.4776	2.5869	2.6799
0.70	0.9865	1.1140	1.2193	1.3052	1.3760	1.4349	1.4850
0.80	0.5133	0.5771	0.6297	0.6725	0.7078	0.7372	0.7622
0.85	0.3442	0.3862	0.4208	0.4489	0.4721	0.4914	0.5078
0.90	0.2066	0.2313	0.2516	0.2682	0.2818	0.2931	0.3028
0.95	0.0936	0.1046	0.1136	0.1209	0.1270	0.1320	0.1362
0.97	0.0541	0.0604	0.0655	0.0697	0.0732	0.0760	0.0785
0.99	0.0174	0.0194	0.0210	0.0224	0.0235	0.0244	0.0252

Table III

Ideal Thrust Coefficient, C_{T_i}, for FIVE-BLADED Propellers

η_i \ λ_i	3.0	3.5	4.0	4.5	5.0	5.5	6.0
				$x_h = 0.2$			
0.50	4.0250	4.5214	4.9182	5.2370	5.4954	5.7070	5.8817
0.60	2.2915	2.5606	2.7748	2.9465	3.0855	3.1991	3.2928
0.70	1.2932	1.4377	1.5524	1.6440	1.7181	1.7785	1.8283
0.80	0.6756	0.7475	0.8043	0.8496	0.8861	0.9158	0.9403
0.85	0.4540	0.5012	0.5383	0.5679	0.9917	0.6111	0.6271
0.90	0.2731	0.3007	0.3225	0.3398	0.3537	0.3650	0.3743
0.95	0.1239	0.1362	0.1458	0.1534	0.1595	0.1645	0.1686
0.97	0.0716	0.0786	0.0841	0.0885	0.0920	0.0948	0.0972
0.99	0.0230	0.0253	0.0270	0.0284	0.0295	0.0304	0.0311
				$x_h = 0.3$			
0.50	3.7814	4.2462	4.6164	4.9124	5.1510	5.3456	5.5054
0.60	2.1482	2.4001	2.6001	2.7597	2.8881	2.9929	3.0788
0.70	1.2098	1.3451	1.4522	1.5375	1.6060	1.6619	1.7077
0.80	0.6309	0.6981	0.7512	0.7934	0.8272	0.8547	0.8773
0.85	0.4236	0.4676	0.5024	0.5299	0.5520	0.5700	0.5847
0.90	0.2545	0.2804	0.3007	0.3168	0.3297	0.3402	0.3488
0.95	0.1154	0.1268	0.1358	0.1429	0.1486	0.1533	0.1570
0.97	0.0667	0.0732	0.0784	0.0824	0.0857	0.0883	0.0905
0.99	0.0214	0.0235	0.0252	0.0264	0.0275	0.0283	0.0290
				$x_h = 0.4$			
0.50	3.4165	3.8451	4.1876	4.4638	4.6862	4.8678	5.0180
0.60	1.9362	2.1689	2.3545	2.5040	2.6242	2.7223	2.8035
0.70	1.0879	1.2132	1.3128	1.3930	1.4574	1.5100	1.5535
0.80	0.5660	0.6284	0.6780	0.7178	0.7497	0.7758	0.7973
0.85	0.3796	0.4206	0.4530	0.4791	0.5000	0.5171	.5312
0.90	0.2279	0.2519	0.2710	0.2862	0.2985	0.3085	0.3168
0.95	0.1032	0.1139	0.1223	0.1290	0.1345	0.1389	0.1425
0.97	0.0996	0.6572	0.0705	0.0744	0.0775	0.0800	0.0821
0.99	0.0192	0.0211	0.0226	0.0239	0.0248	0.0256	0.0263

Table IV

Ideal Thrust Coefficient, C_{T_i}, for SIX-BLADED Propellers

x / $1/\lambda_i$	3.0	3.5	4.0	4.5	5.0	5.5	6.0
			$x_h = 0.2$				
0.50	4.2048	4.6913	5.0764	5.3830	5.6296	5.8298	5.9942
0.60	2.3934	2.6564	2.8639	3.0285	3.1607	3.2679	3.3558
0.70	1.3505	1.4914	1.6021	1.6897	1.7599	1.8167	1.8632
0.80	0.7054	0.7753	0.8300	0.8731	0.9076	0.9354	0.9582
0.85	0.4740	0.5198	0.5555	0.5836	0.6061	0.6242	0.6390
0.90	0.2851	0.3119	0.3328	0.3492	0.3622	0.3728	0.3814
0.95	0.1294	0.1412	0.1504	0.1576	0.1634	0.1680	0.1718
0.97	0.0748	0.0816	0.0868	0.0909	0.0942	0.0969	0.0990
0.99	0.0240	0.0262	0.0279	0.0292	0.0302	0.0310	0.0317
			$x_h = 0.3$				
0.50	3.9806	4.4350	4.7912	5.0731	5.2981	5.4794	5.6269
0.60	2.2612	2.5067	2.6985	2.8499	2.9706	3.0678	3.1467
0.70	1.2734	1.4048	1.5071	1.5878	1.6519	1.7035	1.7453
0.80	0.6640	0.7291	0.7796	0.8193	0.8508	0.8761	0.8967
0.85	0.4458	0.4884	0.5214	0.5472	0.5678	0.5843	0.5976
0.90	0.2678	0.2928	0.3121	0.3272	0.3392	0.3488	0.3565
0.95	0.1214	0.1325	0.1410	0.1476	0.1529	0.1571	0.1605
0.97	0.0702	0.0765	0.0813	0.0851	0.0881	0.0906	0.0925
0.99	0.0226	0.0246	0.0261	0.0273	0.0283	0.0290	0.0296
			$x_h = 0.4$				
0.50	3.6407	4.0593	4.3880	4.6473	4.8542	5.0212	5.1583
0.60	2.0633	2.2897	2.4671	2.6069	2.7183	2.8061	2.8819
0.70	1.1593	1.2807	1.3756	1.4502	1.5097	1.5576	1.9969
0.80	0.6031	0.6634	0.7104	0.7473	0.7766	0.8002	0.8196
0.85	0.4045	0.4440	0.4747	0.4988	0.5180	0.5334	0.5460
0.90	0.2428	0.2659	0.2839	0.2980	0.3092	0.3182	0.3256
0.95	0.1100	0.1202	0.1281	0.1344	0.1393	0.1433	0.1465
0.97	0.0635	0.0694	0.0739	0.0775	0.0803	0.0826	0.0844
0.99	0.0204	0.0223	0.0237	0.0248	0.0257	0.0265	0.0270

Appendix B

Curves of $C_{T_i} - \eta_i - \lambda$ for 3,4,5 and 6 bladed propellers

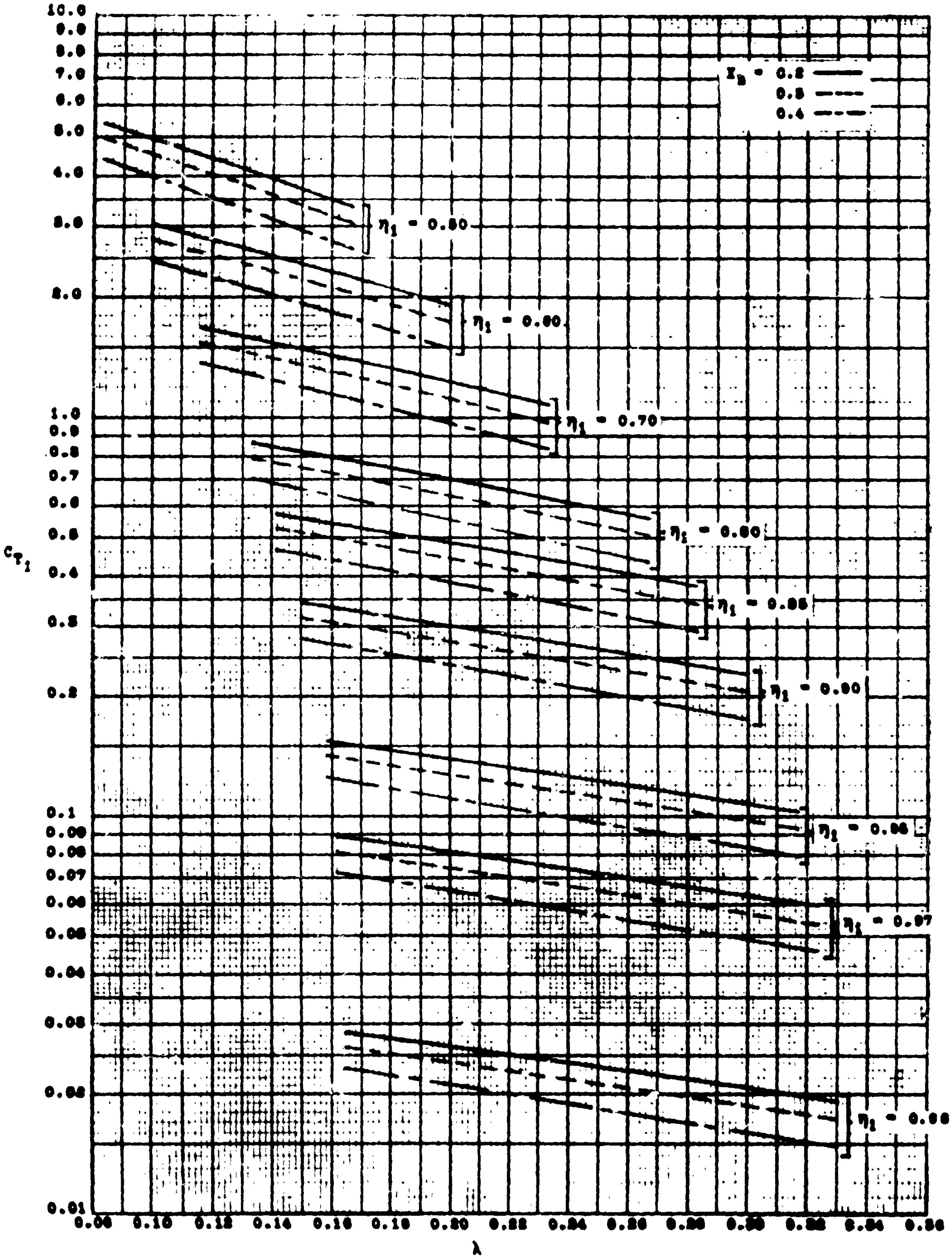

FIG 1 C_{T_i} - η_i - λ Relationship for THREE-BLADED Propellers

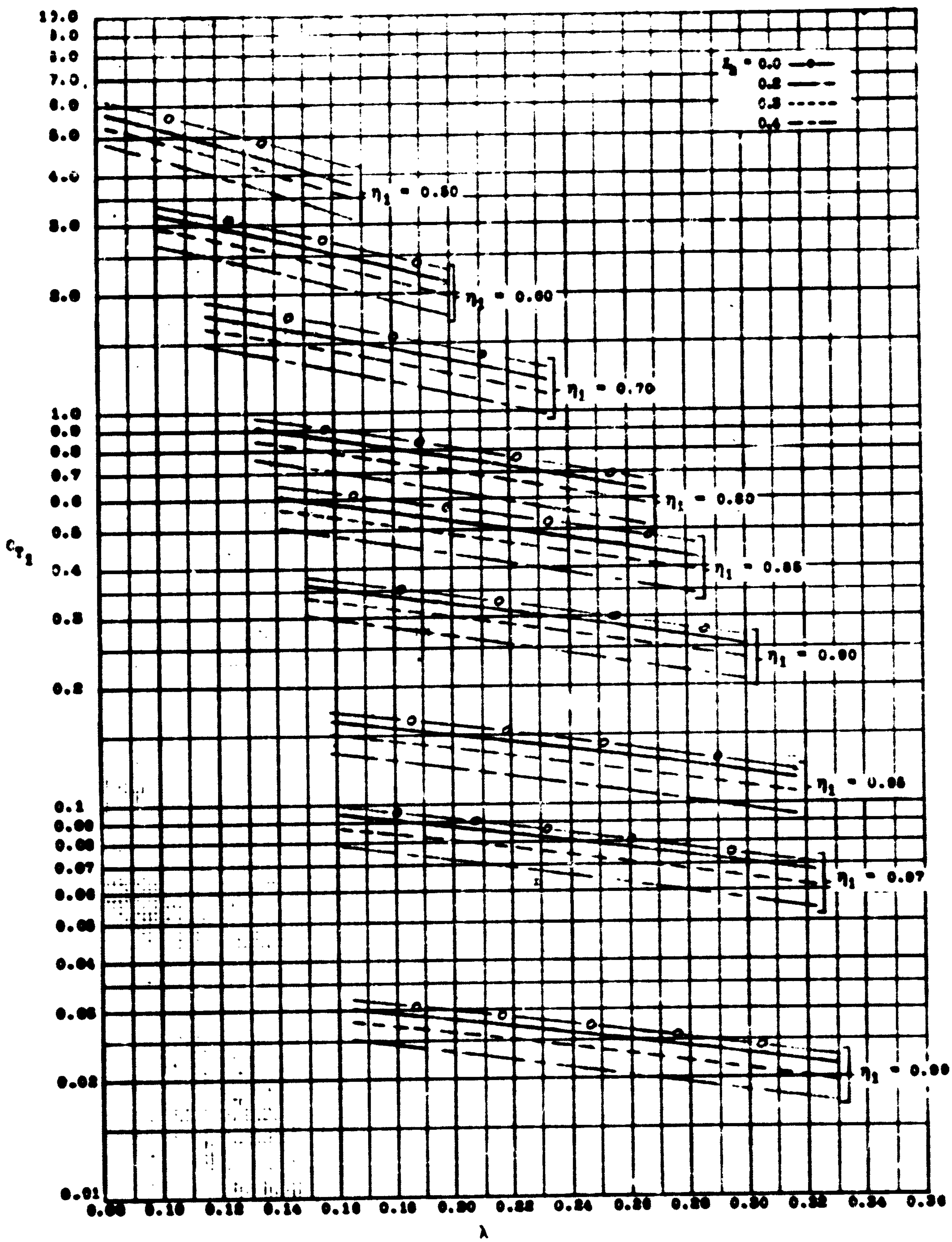

FIG 2 C_{T_1} - η_1 - λ Relationship for FOUR-BLADED Propellers

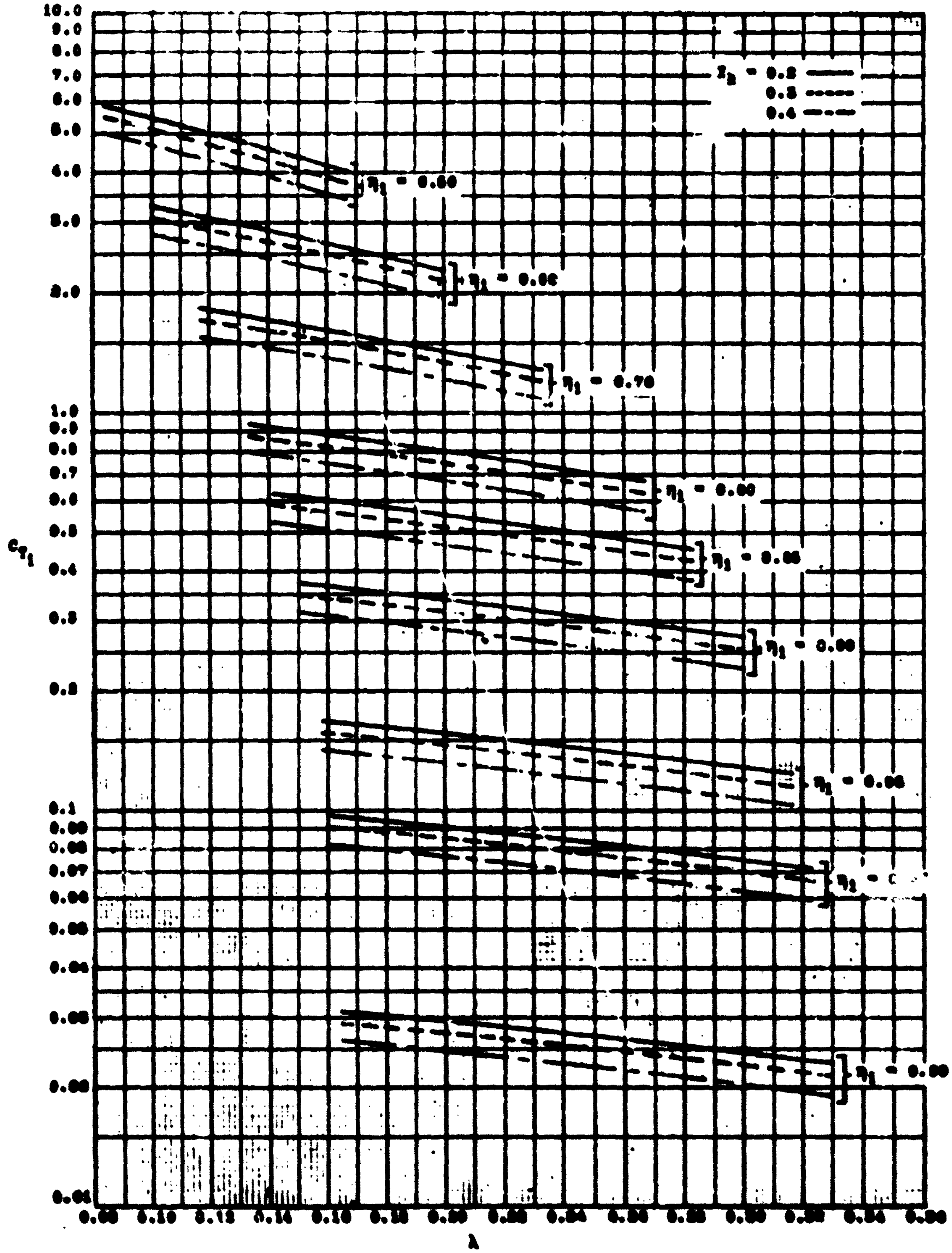

FIG 8 C_{T_1} - η_1 - λ Relationship for FIVE-BLADED Propellers

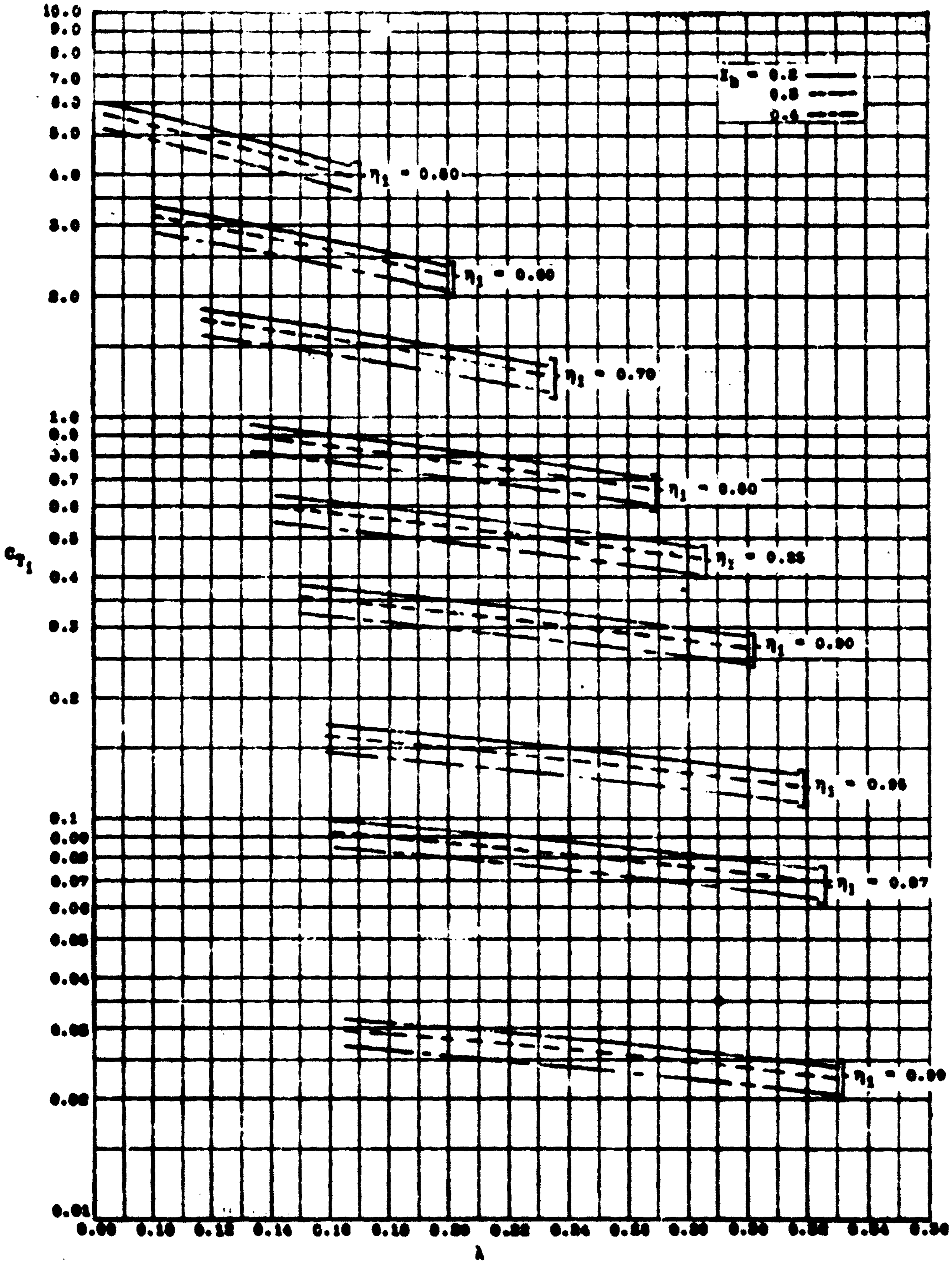

FIG 6 C_{T_i} - η_i - λ Relationship for SIX-BLADED Propellers

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1. Propellers (Marine) – Thrust – Mathematical analysis
2. Propeller blades (Marine)
3. Propeller hubs
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